Abstract. In the radio – host galaxy optical luminosity plane FR I and FR II radio–galaxies are clearly divided. Since the optical luminosity of an elliptical galaxy is an indication of the mass of its central black hole, we propose that the FR I–FR II dividing luminosity is a function of the mass of the black hole powering the active nucleus. Furthermore, as the radio power gives an estimate of the total kinetic power carried by the jet, the FR I–FR II separation can be re–interpreted as occurring at a constant ratio between the jet power and the black hole mass. There is also convincing evidence of a correlation between the radio power and the luminosity in narrow emission lines. As the latter results from photoionization by the radiation produced by accretion, we can estimate the ionizing luminosity and find that the separation luminosity can be also re–expressed as a constant accretion rate between $\sim 10^{-2}$–10^{-3} of the Eddington one. This possibly regulates the accretion mode and the consequent presence and characteristics of nuclear outflows.

Key words: Galaxies: jets — Galaxies: nuclei — Radio continuum: galaxies

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ASTRONOMY AND ASTROPHYSICS

The dividing line between FR I and FR II radio–galaxies

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1. Introduction

Among the strongest phenomenological clues on radio sources origin and physics is the recognition by Fanaroff & Riley (1974) that the majority of radio galaxies can be classified into two morphological types (FR I and FR II) according to where most of the luminosity is radiated, i.e. edge darkened and edge brightened sources, and that this division rather neatly translates into a separation in radio power (respectively below and above $L_{178} \simeq 2.5 \times 10^{33} h_{50}^{-2}$ erg s^{-1} Hz^{-1} at 178 MHz). This division has become even clearer and sharper when it has been found by Ledlow & Owen (1994, 1996) to be a function of the optical luminosity of the host galaxy, in the sense of increasing dividing radio luminosity with increasing optical luminosity of the host.

These pieces of evidence have prompted several physical interpretations, which invoke either or both the interaction of the jet with the ambient medium or/and nuclear intrinsic properties of the accretion and jet formation processes. Among the former models the duality has been attributed to the dynamics of a slowing jet in the ambient gas pressure (either the whole jet or only the hot spot advance, Bicknell 1995; Gopal–Krishna & Wiita 1988, 2001), while the latter ones include the possible different content of the jet plasma (electron–positron pairs or normal electron–proton plasma), or the black hole spin (Reynolds et al. 1996; Baum et al. 1995; Meier 1999).

However there is a further ingredient which can be added to this picture, namely the possibility of associating an estimate of the central black hole mass to both the luminosity of the bulge component in the host galaxies, as proposed by Kormendy & Richstone (1995) and by Magorrian et al. (1998), and the galaxy stellar velocity dispersion following the work by Ferrarese & Merrit (2000) and Gebhardt et al. (2000). This information is a powerful new tool for tackling the long standing problem of the black hole/galaxy formation, and also provides us with elements to estimate the combination of accretion rate and radiative efficiency of the nucleus of the active galaxies.

Interesting results have been already found in this context in connection with the radio quite vs radio loud (possible) dichotomy, where the latter objects appear to be associated with higher mass black holes when objects of the two classes are chosen to have similar optical nuclear (AGN) luminosity (McLure & Dunlop 2001).

Here, we focus on the issue of the dichotomy between FR I vs FR II radio–galaxies in the radio power – host galaxy magnitude plane, taking advantage of the new information on the black hole mass and the indications of connections between the observed radio luminosity and the intrinsic jet power and the luminosity dissipated in the accreting matter flow. In other words through these correlations we translate the separation between FR I and FR II into a critical value of the mass accretion rate.

The key steps (and assumptions) of our derivation are the following. (i) The conversion between host optical magnitude and black hole mass; (ii) the association of the radio luminosity to the jet kinetic power; (iii) the connection of the radio luminosity with the optical luminosity responsible for the photoionization of the [OII] narrow emission lines. The details and results for each of these three steps are the content of the next section. In Section 3 we discuss our findings and in Section 4 we present our conclusions.

2. The FR I–FR II dividing line

2.1. Host optical luminosity and black hole masses

For the conversion of host galaxy optical magnitude into central black hole mass $M_{\rm BH}$ we adopt the relation presented in McLure & Dunlop (2001). Specifically this is expressed in terms of the absolute optical R–band magnitude of the host galaxy $M_{\rm R}$ as

$$\log(M_{\rm BH}/M_\odot) = -0.62(\pm 0.08)\, M_{\rm R} - 5.41(\pm 1.75). \qquad (1)$$

By applying this correlation the range of absolute magnitudes of Fig. 1 can be immediately re–expressed as a range of black hole masses. We report in Fig. 1 the original plot presented by Ledlow & Owen (1996) with the mass reported on the upper x–axis. The dividing radio power between FR I and FR II results to be a linear (within the errors) function of the black hole mass. In other words for any given radio luminosity an FR I morphology tends to be systematically associated with the more massive black holes.

In the following we use the connection between the jet radio power and intrinsic nuclear luminosities. For an assumed efficiency this will allow us to re-express the radio luminosity

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vs host galaxy magnitude plane in terms of mass accretion rate vs black hole mass.

2.2. Relation between radio luminosity and jet power

Let us then start considering the relation between radio power and kinetic power output of the jet. It has been found that the radio luminosity gives an estimate of the average power transported by the jet to the outer lobes. In particular, several authors (Rawlings & Saunders 1991; Rawlings 1992; Willott et al. 1999) have found significant correlations between the radio luminosity (and/or the luminosity in narrow lines) and the jet kinetic power $L_{\rm jet}$. Here we have adopted the correlation reported by Willott et al. (1999), namely:

$$L_{\rm jet} = 3\times 10^{21} L_{151}^{6/7} \ \ {\rm erg\,s^{-1}}, \qquad (2)$$

where L_{151} [erg s^{-1} Hz^{-1} sr^{-1}] is the monochromatic radio power at 151 MHz. To convert this into a luminosity at 1.4 GHz (in W Hz^{-1}) we have assumed a radio spectral index $\alpha = 0.8$ [$L(\nu)\propto\nu^{-\alpha}$] [1]. We can thus determine the relation between $L_{\rm jet}$ and $M_{\rm BH}$. In Fig. 1 we show the resulting $L_{\rm jet}$ on the right hand side y–axis. It becomes apparent that the division between FR I and FR II corresponds to a separation at $\sim$ *constant* $L_{\rm jet}/M_{\rm BH}$. Quantitatively this can be expressed as

$$L_{\rm jet} \simeq 0.015 L_{\rm Edd}, \qquad (3)$$

where $L_{\rm Edd} = 1.3\times 10^{38}(M_{\rm BH}/M_\odot)$ erg s^{-1} is the Eddington luminosity.

2.3. Relation between radio luminosity and accretion luminosity

Finally, let us estimate the nuclear radiative output, by considering the well established relation between the luminosity in narrow emission lines, believed to result from photoionization by the nuclear (accreting) radiation $L_{\rm ion}$, and the radio power. This appears to be particularly significant in the case of the [OII] emission - while part of the [OIII] luminosity might be affected by obscuration (Baum & Heckman 1989, Browne & Jackson 1992, but see also Jackson & Rawlings 1997). This relation has been presented by several authors (Saunders et al. 1989, Rawlings 1992, Willott et al. 1999). We consider here again the results by Willott et al. (1999) and adopt the relation

$$L_{\rm ion} \sim 5\times 10^3\, L_{151}. \qquad (4)$$

Through that, we simply convert the radio luminosity into an estimate of $L_{\rm ion}$ as shown in Fig. 2. The division between FR I and FR II then turns out to be a separation at *constant* $L_{\rm ion}/M_{\rm BH}$ and more precisely is described by the relation

$$L_{\rm ion} \sim 6\times 10^{-3} L_{\rm Edd}. \qquad (5)$$

3. Discussion

We find that the separation in FR I/FR II morphology and power appears to occur at a certain value of the luminosity over black hole mass ratio. Although we neglected the significant

[1] We have also taken into account the different value of H_0 used in Willott et al. (1999) and in Ledlow & Owen (1996).

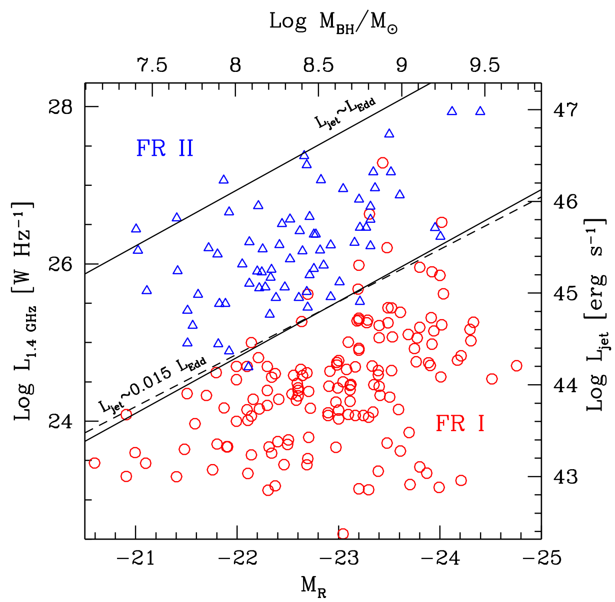

Fig. 1. The radio jet power – host optical magnitude plane with the line dividing FR I from FR II (dashed line, from Ledlow & Owen 1996). Triangles: FR II; circles: FR I. The two axis have been re–expressed as jet power vs black hole mass (right and upper axis). The two diagonal solid lines represent $L_{\rm jet} = 0.015 L_{Edd}$ and $L_{\rm jet} = L_{\rm Edd}$.

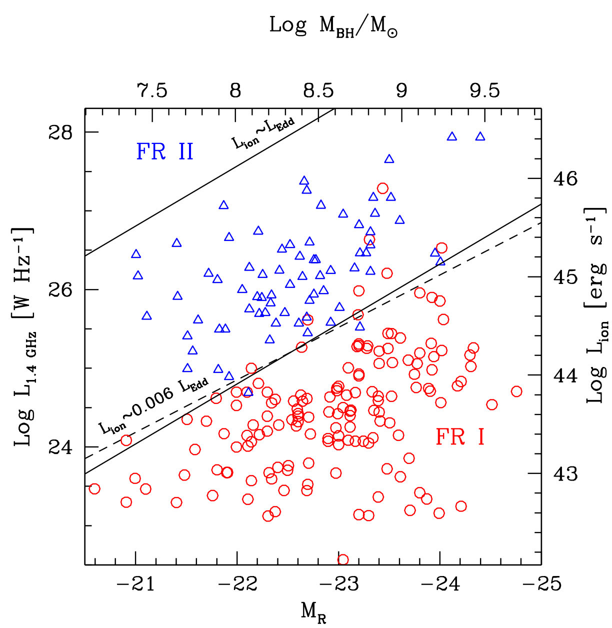

Fig. 2. The radio jet power – host optical magnitude plane with the line sharply dividing FR I from FR II (dashed line, from Ledlow & Owen 1996). According to reasonably well established correlations this plane is equivalent to an accretion power vs black hole mass plane (right and upper axis). The central diagonal line represents $L_{\rm ion}\sim 6\times 10^{-3} L_{\rm Edd}$.

dispersions of the assumed correlations, note that these would imply a fuzzier separation between the two classes, but would not alter the average behaviour we consider here. In the following we speculate about possible interpretations of this finding.

3.1. *Are we finding a critical value of $\dot{m}$ where the accretion mode changes?*

It is tantalizing to speculate that the primary reason of the FR I–FR II dichotomy lies in the different nature of their accretion disks. The found value of $L_{\rm ion}/L_{\rm Edd} \sim 6\times 10^{-3}$ suggests a critical value of $\dot{m}$, the accretion rate in Eddington units, for which the mode of accretion changes (within the uncertainties of the above correlations, e.g. Willot et al. 1999). This change might correspond to the transition from a standard optically thick geometrically thin efficient Shakura–Sunyaev (1973) disk to a radiatively inefficient optically thin flow as an ion supported torus (Rees et al. 1982) in the form of e.g. an advection dominated accretion flow (ADAF, see e.g. Narayan, Garcia & McClintock 1997), adiabatic inflow–outflow (ADIOS, Blandford & Begelman 1999) or a convection dominated flow (CDAF, Narayan, Igumenshchev & Abramowicz 2000).

If $L_{\rm ion}$ originates by the dissipation of the accretion power, $L_{\rm ion}\sim L_{\rm disk}=\eta \dot{M}_{\rm acc}c^2$ and if the efficiency η is constant, at least within the FR II population, we have that the FR I–FR II division line is quantitatively described by

$$\dot{m} \,\equiv\, \frac{\dot{M}_{\rm acc}}{\dot{M}_{\rm Edd}} \,\sim\, 6\times 10^{-2}\eta_{-1}^{-1}, \qquad (6)$$

where $\dot{M}_{\rm Edd}\equiv L_{\rm Edd}/c^2$ and $\eta = 0.1\eta_{-1}$. Note that, within the sample considered by Ledlow & Owen (1996), the radio galaxies span a wide range of $\dot{m}$, between $\dot{m}\sim 10^{-4}$ and ~ 10, and nevertheless such transition has to be rather sharp in order to produce such a well defined dividing line.

But how could be the accretion mode affect the large scale structure of the radio galaxies?

Observationally, we know that the structures of the parsec scale jet of FR I and FR II are very similar and no difference in their velocities appears to be present at these scales (e.g. Giovannini et al. 2001). On the other hand, it is believed that on the kpc scale FR I jets have velocities smaller than FR II jets (e.g. Begelman 1982, Bicknell 1984, Laing 1993): mildly relativistic transonic jets could be more subject to Kelvin–Helmoltz instabilities, leading to the typical FR I morphology (it is conceivable that the deceleration is first due to the interaction with circum–jet material). However it is not clear at what scale an FR I jet decelerates. Indeed, high values of the bulk Lorentz factor Γ ($\sim$ 10–15) are required to account for the spectral energy distribution of high energy peak BL Lac objects (HBL) which are believed to be FR I whose jet is aligned with the line of sight (Ghisellini et al., 1998; Tavecchio et al., 1998). But the very same objects do not show the extreme superluminal motion seen in the more powerful blazars thought to be FR II seen end–on (see e.g. Marscher 1999, Jorstad et al. 2001). It is thus possible that either deceleration occurs between say a fraction of a parsec, where most of the emission is produced, and the VLBI parsec scale, or that HBL are preferentially seen at angles smaller than $1/\Gamma$ (resulting in a lower apparent superluminal velocity). Independently of the cause, in this scenario FR I jets start highly relativistic and decelerate between the subpc and the kpc scales. Indeed this is a crucial ingredient in the model proposed by Bicknell (1995), who points to the environment and the consequent deceleration as the main cause of the FR I–FR II dichotomy.

In this context, our findings suggest that it might be also the accretion process itself to play a key role in the deceleration and dichotomic behaviour, by affecting the pc–kpc scale environment. Although at this point it might be premature to single out a consistent model linking the accretion mode and the jet behaviour on the pc–kpc scale, one could speculatively attribute it to the presence of a wind – produced by the disk itself and interacting with and slowing down the relativistic jet – becoming more important for lower accretion rates, as predicted by some accretion scenarios (see above and also numerical simulations by Stone, Pringle & Begelman 1999). We can only speculate about the expected signatures of the interaction of a wind and a relativistic jet. This might lead to the formation of shocks (similar to the analog *external shocks* in gamma-ray bursts) and the efficient conversion of the bulk kinetic energy into radiation (see e.g. Dermer 1999). FR I radio galaxies – and their aligned counterparts BL Lacs – could therefore be more efficient radiators than FR II radio galaxies and emission line blazars (although with a smaller absolute emitted power).

Since for a given mass the accretion luminosity in low radiative efficiency flows is expected to increase with $\dot{M}_{\rm acc}^2$ (see e.g. Narayan, Garcia & McClintock, 1997) this scenario can naturally account for the lack of intense broad emission lines in FR I sources and BL Lac objects (but allowing some sources, as BL Lac itself, to show broad emission lines, albeit weak). Note that in this case the absence of broad lines would not be ascribed to obscuration (which remains a possibility in FR II sources), but to the weak level of the ionizing continuum, as suggested by the detection of non–thermal nuclei in HST images of FR I sources (Chiaberge, Capetti & Celotti 2000).

4. Conclusions

We have shown that the FR I–FR II dividing line in the radio luminosity vs optical host galaxy luminosity can be re–expressed as a line of constant ratio between the jet and/or the disk accretion power and the Eddington luminosity. This suggests that the FR I–FR II dichotomy could be controlled by the properties of the underlying accretion process more than (or in addition to) a different environment.

The specific value of the division, $L_{\rm ion}\sim 6\times 10^{-3}L_{\rm Edd}$, could correspond to a change in the accretion mode.

Since FR I have, on average, larger black hole masses, they might be older or have accreted at a greater rate in the past (through e.g. mergings), and therefore it is conceivable to argue that at least a fraction of them were FR II radio–galaxies in the past. This might account for the different evolution properties of the two classes (see e.g. Urry & Padovani 1995).

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References

Baum S. A., Zirbel E.L. & O'Dea C.P., 1995, ApJ 451, 88
Baum S. A. & Heckman T.M., 1989, MNRAS, ApJ, 336, 702
Begelman M.C., 1982, IAU Symp 97, Extragalactic Radio Sources, Heeschen D.S., Wade C.M., eds., Kluwer, p. 223
Bicknell G.V., 1984, ApJ, 286, 68
Bicknell, G.V., 1995, ApJSS, 101, 29
Blandford R.D. & Begelman M.C., 1999, MNRAS, 303, L1
Browne I.W.A., Jackson N., 1992, in Physics od Active Galactic Nuclei, W. Duschl, S. Wagner, eds., Springer, 61
Chiaberge M., Capetti A., Celotti A. 2000, A&A, 355, 873
Dermer C.D., 1999, in TeV Astrophysics of extragalactic sources, Catanese M. & Weekes T. Eds, Astroparticle Physics, 11, 1
Fanaroff B.L. & Riley J.M., 1974, MNRAS 167, 31p
Ferrarese L. & Merrit D., 2000, ApJ, 539, L9
Gebhardt K., Bender, R., Bower G. et al., 2000, ApJ, 539, L13
Ghisellini G., Celotti A., Fossati G., Maraschi L. & Comastri A., 1998, MNRAS, 301, 451
Giovannini G., Cotton W.D., Feretti L., Lara L. & Venturi T., 2001, ApJ, 552, 508
Gopal–Krishna & Wiita P.J. , 2001, A&A, 373, 100
Gopal–Krishna & Wiita P.J. , 1988, Nature, 333, 49
Jackson N. & Rawlings S., 1997, MNRAS, 286, 241
Jorstad S.G., Marscher A.P., Mattox J.R., Wehrle A.E., Bloom S.D. & Yurchenko A.V., 2001, ApJS, 134, 181
Kormendy J. & Richstone D., 1995, ARAA, 33, 581
Laing R.A., 1993, Astrophysical Jets, Burgarella D., Livio M., O'Dea C., eds, Cambridge University Press, 95
Ledlow M.J. & Owen F.N., 1994, in The Physics of Active Galaxies. ASP Conference Series, Vol. 54, G.V. Bicknell, M.A. Dopita, and P.J. Quinn Eds., p. 319
Ledlow M.J. & Owen F.N., 1996, AJ, 112, 9
Magorrian J., Tremaine S., Richstone D. et al., 1998, AJ, 115, 2285
Marscher A.P., 1999, in TeV Astrophysics of extragalactic sources, Catanese M. & Weekes T. Eds, Astroparticle Physics, 11, 19
McLure R.J. & Dunlop J.S., 2001, MNRAS, in press (astrop–ph/0009406)
Meier D.L., 1999, ApJ, 522, 753
Narayan R., Garcia M.R. & McClintock J.E., 1997, ApJ, 478, L79
Narayan R., Igumenshchev I.V. & Abramowicz M.A., 2000, ApJ, 539, 798
Rawlings S.G. & Saunders R.D.E., 1991, Nature, 349, 138
Rawlings S.G., 1992, in Extragalactic radio sources – From beams to jets. Editors, J. Roland, H. Sol, G. Pelletier; CUP p. 332
Reynolds C.S., Fabian A.C., Celotti A. & Rees M.J., 1996, MNRAS, 283, 873
Rees M.J., Begelman M.C., Blandford R.D. & Phinney E.S., 1982, Nature, 295, 17
Saunders R.D.E, Baldwin, J. E., Rawlings S., Warner P.J., Miller L., 1989, MNRAS, 238, 777
Shakura N.I. & Sunyaev R.A., 1973 A&A, 24, 337
Stone J.M., Pringle J.E., Begelman M.C., 1999, MNRAS, 310, 1002
Tavecchio F., Maraschi L. & Ghisellini G., 1998. ApJ, 509, 608
Urry C.M. & Padovani P., 1995, PASP, 107, 803
Willott C.J., Rawlings S. Blundell K.M. & Lacy M., 1999, MNRAS, 309, 1017